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Research and Development Technical Report

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FERRITE POWER LIMITER FOR RADIO SET AN/GRC-144

Samuel Dixon, Jr.
Electronics Technology and Devices Laboratory

October 1977

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER (14) ECOM-4541	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) Ferrite Power Limiter For Radio Set AN/GRC-144.		5. TYPE OF REPORT & PERIOD COVERED Technical - July 75-July 77
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Samuel/Dixon, Jr		8. CONTRACT OR GRANT NUMBER(s) (9) Research and development technical rept. Jul 75 - Jul 77,
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Electronic Technology & Devices Lab., DRSEL-TL-MM Fort Monmouth, New Jersey 07703		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6.27.05.A (16) 1L762705 A H94 A1
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Electronic Technology and Devices Lab., DRSEL-TL-MM Fort Monmouth, New Jersey 07703		12. REPORT DATE (11) October 1977 (12) A1
		13. NUMBER OF PAGES 14 pgs
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 18p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Statement A: Approved for Public Release; Distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Microwave devices, Ferrite Limiters, Frequency selectivity, Subsidiary resonance, Spin waves, Ferrites

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This investigation describes analytical and experimental results obtained on a C-band ferrite limiter which utilizes a YIG rod inserted along the longitudinal axis of a coupled dielectric resonator bandpass structure. This device is aimed at providing receiver front-end protection for communication systems such as the AN/GRC-144 which operate in a dense, high signal power environment. By utilizing a long, thin, single crystal YIG rod instead of YIG spheres, the limiter dynamic range has been extended from 20 dB to 35 dB. The threshold power varies from 5 dBm at 4.4 GHz to 15 dBm at 5.0 GHz with an insertion loss of less than

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INTRODUCTION

When communication receivers, such as the AN/GRC-144 radio set, with "open" front-ends are deployed in a dense, high-signal power environment they are particularly vulnerable to damage or possible burn-out. Since modern receiver technology employs expensive devices such as tunnel-diode amplifiers, field-effect transistors, and Schottky-barrier mixers, receiver front-end protection is a vital function to insure reliable performance. The present receiver in the Radio Set AN/GRC-144 has the rf input channeled through a preselector filter and a tunnel-diode amplifier (TDA) with no protection against high-level signals. To protect the receiver TDA from damage and possible burn-out, a broadband, frequency-selective ferrite limiter is required; moreover, such a limiter can provide this receiver protection while still allowing frequency agility.

Recent advancements [1,2] in the state-of-the-art in frequency-selective ferrite limiters have significantly increased their utility as practical receiver protectors. These advancements have demonstrated that the subsidiary resonance phenomena[3], with its inherent high-threshold power level, can be used effectively in the design of low power-level ferrite limiters. The high power needed in the past to initiate subsidiary resonance in the ferrite has been considerably reduced by the use of high permittivity, dielectric resonators. These high "Q" dielectric resonators can provide concentrated rf electro-magnetic fields with low power input, and thereby reduce the power limiting level to a more practical value (i.e. milliwatts).

However, in order to sufficiently protect the receiver front-end in a dense, high signal power environment from most potential threats, the dynamic range or power handling capability should be as high as possible while maintaining an acceptable insertion loss. Previous limiters using the dielectric resonator structure have exhibited a dynamic range of about 20 dB, which results from the fact that the small YIG spheres used as the active elements did not have the volume necessary to limit rf signals over a broad power range. The present development effort has succeeded in increasing the dynamic range by utilizing a low-linewidth YIG rod as the power limiting element.

DISCUSSION

The main thrust in the development of a frequency-selective subsidiary resonance limiter for application to the AN/GRC-144 radio set has been in devising a limiter design that would yield a minimum threshold power level while extending the power handling capability of the device.

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1. S. S. Elliott, AIP Conference Proceedings, No. 18, Part 2, 1273, 1973.
2. S. S. Elliott, S.T.K. Nieh, and O. Wetterhorn, "Broadband Ferrite Limiters," ECOM, Final Report, February 1974, Contract No. DAAB07-72-C-0305.
3. H. Suhl, Phys Review 101, 1437, 1956.

To obtain the low-threshold field, high "Q" dielectric resonators built with single crystal strontium titanate ($SrTiO_3$) were used to intensify the rf field inside the limiting media. $SrTiO_3$ has low loss($\tan \delta = 0.00083$) and a high dielectric constant ($\epsilon_r = 300$). The dielectric resonators have quality factors in the order of 1000. Following the expressions given by Yee[4] and Sethares and Naumenn[5] we obtained the following formulas for $SrTiO_3$.

$$A = 8.83 \times 10^8/f \text{ (cm)} = 3.48 \times 10^8/f \text{ (inch)}$$

$$L = 7.07 \times 10^8/f \text{ (cm)} = 2.78 \times 10^8/f \text{ (inch)}$$

where:

A = radius of the dielectric resonator

L = thickness of the dielectric resonator

f = frequency of the dielectric resonator

The ratio of L/A is normally set at 0.8 to give the best frequency separation of the TE_{ION} mode of operation from higher order modes of the dielectric resonator. The frequency of the next higher order mode is 1.36 times the frequency of the TE_{ION} mode.

In order to place a YIG rod down the center of the dielectric resonators, a 0.035 inch hole is drilled along the center axis of the resonators. The rod diameter at C-band was determined to be 0.032 inch, which is the largest YIG rod that the resonators can effectively accommodate without modifying the resonant frequency of the resonator. In general, the calculated values of A and L are used as a guide since the actual physical dimensions of the resonators are arrived at empirically. The resonant frequency is also effected by the strength of the transversally applied dc magnetic field. Consequently, to accurately determine the resonator resonant frequency requires single resonator limiting level measurements performed first to find the dc magnetic field and then the physical dimensions of the dielectric resonators.

The ferrite limiter applicable to the AN/GRC-144 radio set will require a maximum dynamic range. Using the configuration shown in Figure 1, one can assess the impact on dynamic range of each successive dielectric resonator-YIG sphere combination. Measurements conducted under a previous program have been made on a multiple resonator sphere limiter; starting with 38 YIG spheres and successively removing five spheres at a time, measurement of the power response was performed each time. The results, plotted in Figure 2, show that the dynamic range is a function of the number of spheres whereby the increase in dynamic range starts to approach a limiting value of about

4. H. Y. Yee, W. W. Hansen Lab of Physics Report No. 1065, July 1963
5. J. C. Sethares and S. J. Naumenn, IEEE - MTT 14, 2, 1966.

25 dB. Other parameters effecting the dynamic range are the ferrite sphere size and the resonator hole size. At C-band, two equivalent structures were built with eight YIG spheres, one with 0.040 inch diameter spheres and the other with 0.025 inch spheres; the spheres exhibited approximately the same linewidth (ΔH = 0.3 oersteds). From a power response comparison, shown in Figure 3, it was concluded that the diameter of YIG spheres should be at least 25% of the diameter of the resonator to achieve maximum dynamic range.

A microwave signal incident on the ferrite sample, polarized normal to the dc field, will couple to the uniform precession in the subsidiary resonance region. This process takes place linearly until a certain critical magnetic field intensity h_c, when the uniform precession mode catastrophically excites spin waves at approximately half its frequency $\omega/2$. The appearance of the subsidiary resonance at high power levels is governed by the condition that:

$$\gamma H_{dc} < \frac{\omega}{2} + N_z \omega_m \tag{1}$$

where:

$\omega_m = \gamma 4\pi M$ = saturation magnetization

N_z = demagnetizing factor

H_{dc} = applied dc magnetic field

γ = gyromagnetic ratio.

These restrictions assure that the dc biasing field has been reduced sufficiently so that the half-frequency spin waves required for first order nonlinear process will exist. The minimum value of the biasing field that can be used is that value required to saturate the ferrite, which in turn depends on the shape of the ferrite. When these conditions are satisfied, the threshold field for excitation of half-frequency spin waves is given by the following:

$$h_c = \frac{2\omega \Delta H_k \left[(\omega - \omega_r)^2 + (\gamma \Delta H)^2\right]^{1/2}}{\omega_m \left(\frac{\omega}{2} + \omega_H - N_z \omega_m\right)} \tag{2}$$

where: h_c = critical field

ΔH_k = spin wave linewidth

ω_r = Kittel resonant frequency

ΔH = resonant linewidth

$\omega_H = \gamma H_{dc}$

Although the use of dielectric resonators lowers this critical power level considerably, it is usually necessary to further minimize the above equation. Minimization is accomplished by choosing the right ferrite material and biasing it correctly. For the C-band frequency range, single crystal YIG is superior to any other material, yielding the lowest limiting power level.

EXPERIMENTAL DETAILS

The multiple dielectric-resonator YIG-rod structure, used in this investigation is illustrated in Figure 4. The device dimensions, without the permanent magnet as seen in Figure 5, are 2.5 by 0.5 by 1.25 inches and contains 20 dielectric resonators which are 0.150 inch in diameter and 0.060 inch in thickness. Based on a previous design, the dielectric resonators were coupled periodically and axially spaced to form a bandpass filter which exhibits low loss over a relatively large bandwidth. A long thin single crystal YIG rod is inserted along the center axis of the dielectric resonators to form the limiter device. In this case the YIG rod was about 0.032 inch in diameter and was assembled by butting three 0.5 inch long rods end-to-end.

The TE_{1ON} mode of the cylindrical dielectric resonator is particularly suitable to this application because it has a maximum of magnetic field (and a zero of electric field) at the center of each resonator as shown in Figure 6. The resonators are again single crystal strontium titanate ($SrTiO_3$). One problem with paraelectric materials such as strontium titanate is the high negative temperature coefficient which causes a frequency shift of about 15 MHz/^oC at X-band. This problem can be overcome by overdesigning the device structure to have sufficient bandwidth to compensate for the frequency drift due to temperature changes. The device investigated was designed to have a bandwidth of 1,200 MHz centered at 4.7 GHz, rather than the 600 MHz (4.4 to 5.0 GHz) range of interest at room temperature. The bandwidth of this experimental device compensates for a temperature change of $\pm 20^oC$. A practical device would necessitate having a much greater bandwidth.

Since the desired mode in the dielectric resonator resembles a magnetic dipole, the input and output coupling of microwave energy was accomplished using small, coaxial current loops. The approach, derived experimentally, was to consider the coupling loop and the first resonator as a single resonant system and to center the resonance of this combination in the passband.

As shown in Figure 4, the device is transversely pumped with a magnetic bias field of 1300 gauss which is perpendicular to the axis of the rod. This arrangement results in a compact structure with efficient coupling between the rf field and the single crystal YIG rod.

Parallel pumping with the dc magnetic field parallel to the YIG rod was also investigated. The dynamic range using this configuration was small, in the order of 15 db; therefore, detailed data was not taken since the goal of the project was to extend the power handling capability of the sphere-type ferrite limiter.

EXPERIMENTAL RESULTS

Figure 7 shows the insertion loss and the threshold power measured experimentally as a function of frequency over the range from 4.4 to 5.0 GHz.

The low-power insertion loss is less than 1.0 dB over this range, while the threshold power for the onset of subsidiary-resonance absorption varies from 5 mW at 4.4 GHz to 15 mW at 5.0 GHz. This increase in the limiting power level as a function of frequency is to be expected from theoretical predictions.

Figure 8 is a plot of the peak (leakage) power output as a function of the peak input power for both the YIG sphere and the YIG rod devices at 4.7 GHz. When comparing the limiting power dynamic range, the YIG rod device has an additional 15.0 dB of dynamic range (i.e. 35 dB vs 20 dB). Figure 9 shows the results of threshold power and dynamic range measurements for the YIG rod device at three frequencies, 4.4 GHz, 4.7 GHz, and 5.0 GHz. As can be seen, the power limiting level varies considerably over the bandwidth of the device while the dynamic range stays relatively constant at about 35 dB. The long thin YIG rod increases the ferrite volume in the device structure so that a greatly increased quantity of the ferrite is in the presence of the rf magnetic fields; this enhanced interaction causes an increase in the power handling capability of the device and extends the dynamic range. The experimentally measured threshold power of 10 mW is reasonably close to the calculated threshold power of 2.5 mW at 4.7 GHz.

One problem with all ferrite limiters is the passage of a leading edge "spike" on large signals with a fast rise-time. The origin of this spike leakage is due to the finite rise-time of the nonlinear loss mechanism responsible for the limiting action. The spike duration is minimized when the ferrite material has a relatively large saturation magnetization, a narrow uniform presession linewidth and a narrow spin wave linewidth. For very fast rise-times ($\sim 10^{-9}$ sec), the duration adjusts itself so that the energy is typically 2.0 ergs at C-band.

CONCLUSIONS

The objectives of this experimental development effort were to utilize the highest dielectric constant resonators available with low loss in order to minimize the threshold power and to couple them with a ferrite geometry which would then extend the limiter dynamic range. In an attempt to increase the dynamic range of the YIG sphere-type limiter a trade-off has to be made with respect to insertion loss. The dynamic range levels off at 25 dB as the number of dielectric resonator-sphere combinations are increased; the corresponding insertion loss is about 2.5 dB which is an unacceptable level. Therefore, to maximize the dynamic range, the YIG rod approach was utilized.

The experimental development effort using the YIG rod has shown that it is practical to design frequency-selective ferrite limiters (applicable to the AN/GRC-144 radio set) with a dynamic range substantially greater than was previously possible using the YIG sphere approach. The use of a single crystal YIG rod instead of spheres in the dielectric resonator structure has extended the dynamic range from 20 to 35 dB. This increase in the dynamic range was accomplished with an insertion loss of less than 1.0 dB and a threshold power in the same order of magnitude (10 mW) as the device which used spheres.

Another technique which may expand the dynamic range even further is to utilize the multiple YIG rod structure in a graded threshold approach. In this design the limiting threshold of each rod is successively lower than that of the preceding rod.

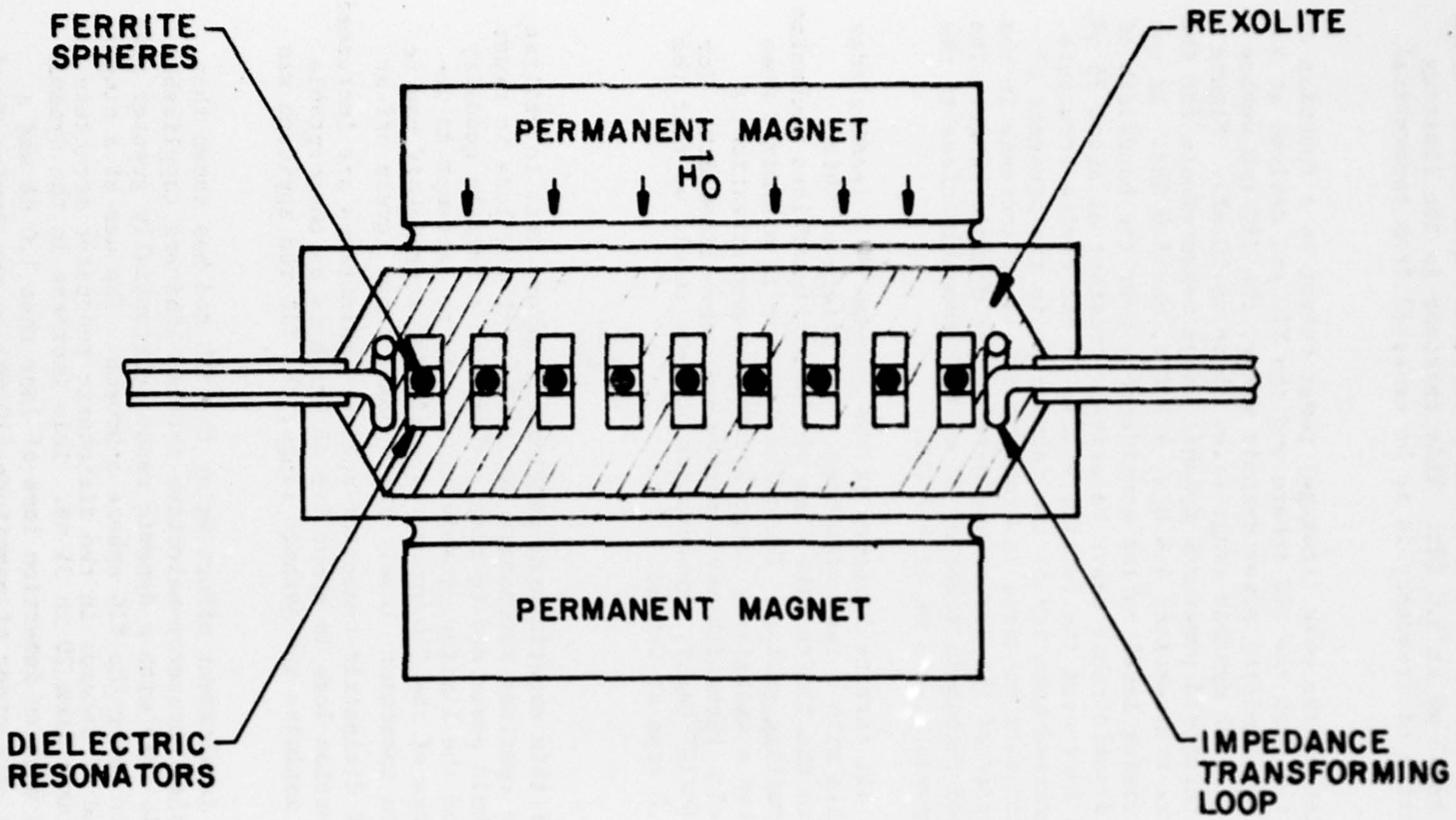

FIGURE 1 BROADBAND FERRITE LIMITER: CROSS SECTION

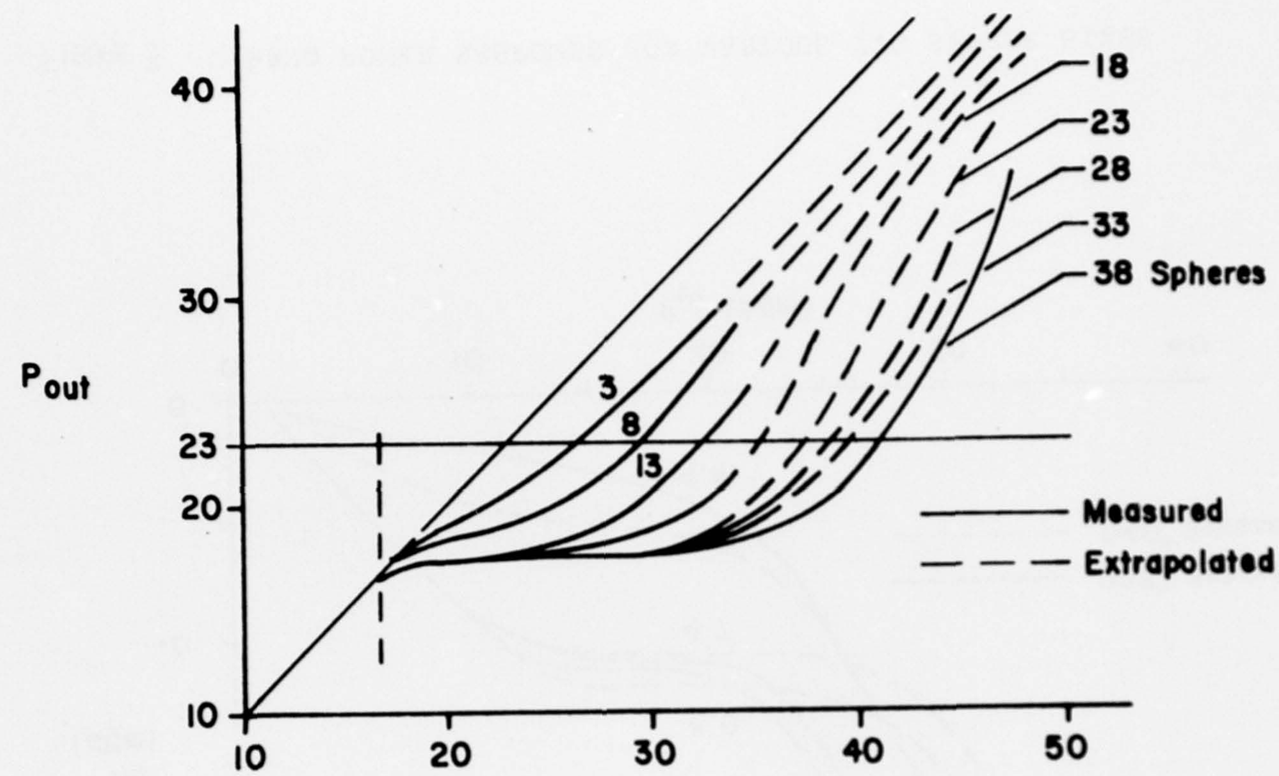

FIGURE 2 DYNAMIC RANGE VS NUMBER OF YIG SPHERES

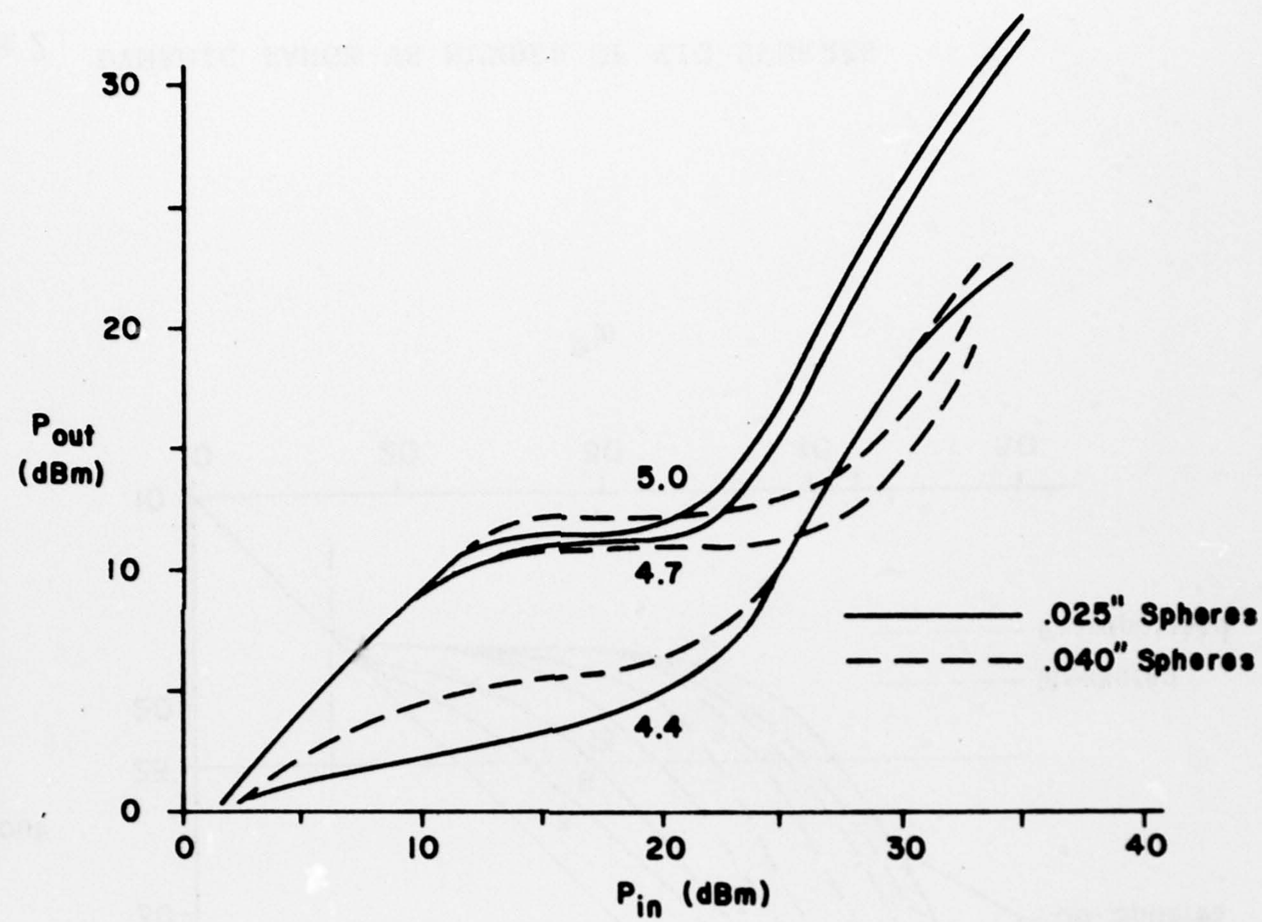

FIGURE 3 C-BAND POWER RESPONSE FOR VARIOUS YIG SPHERE SIZES

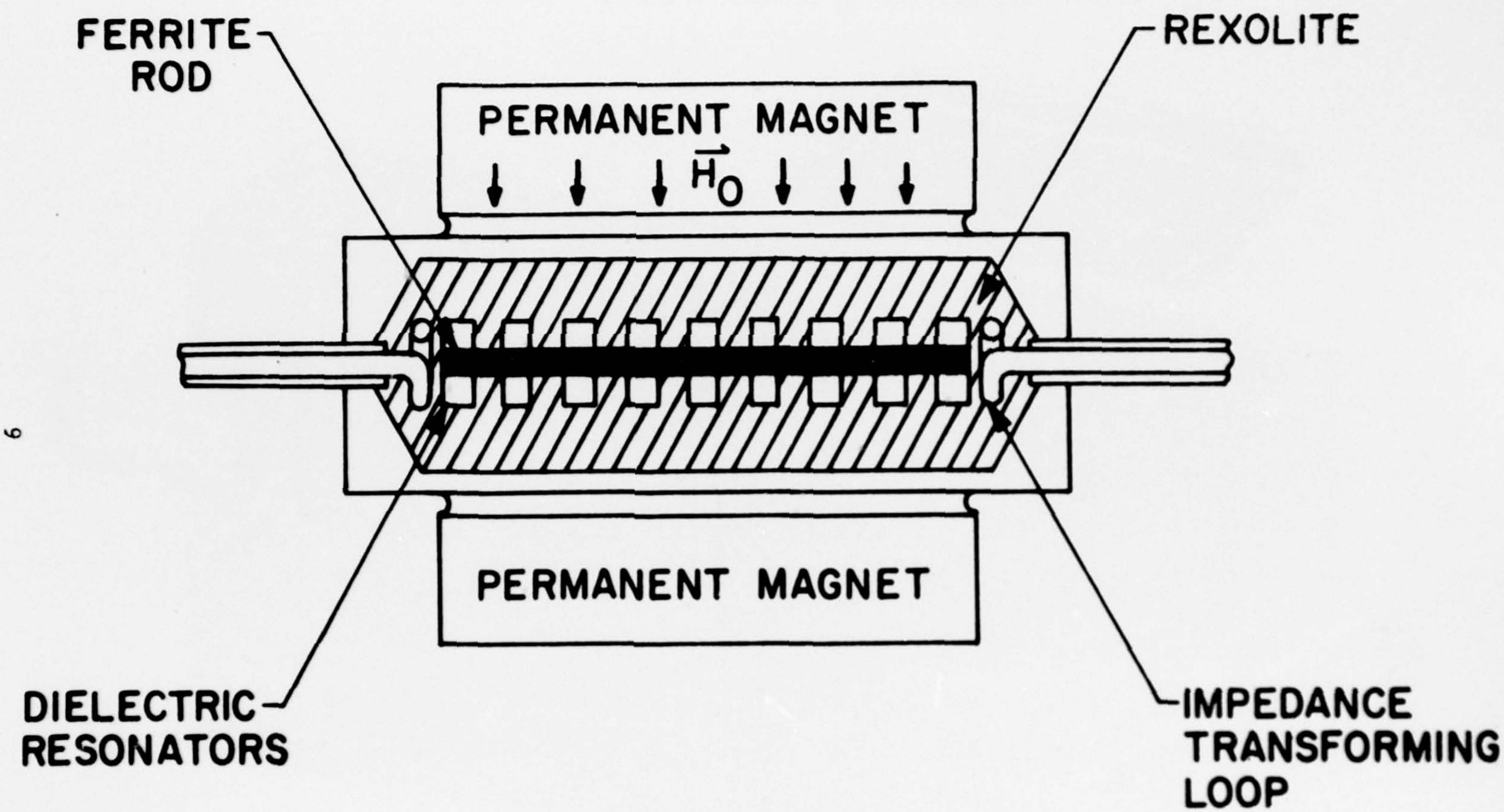

FIGURE 4 - YIG-ROD FERRITE LIMITER

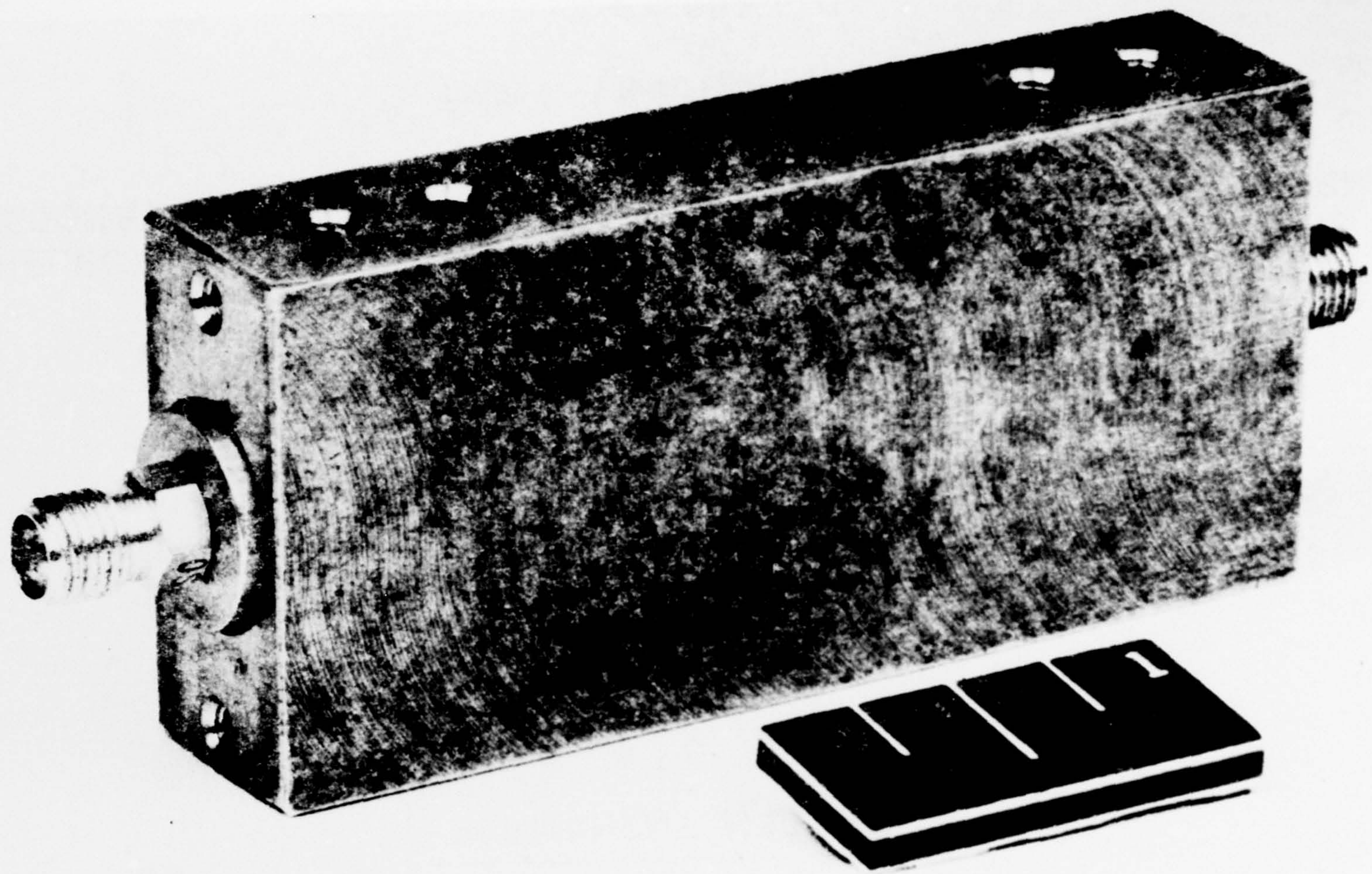

FIGURE 5 - EXTERNAL VIEW OF YIG-ROD FERRITE LIMITER

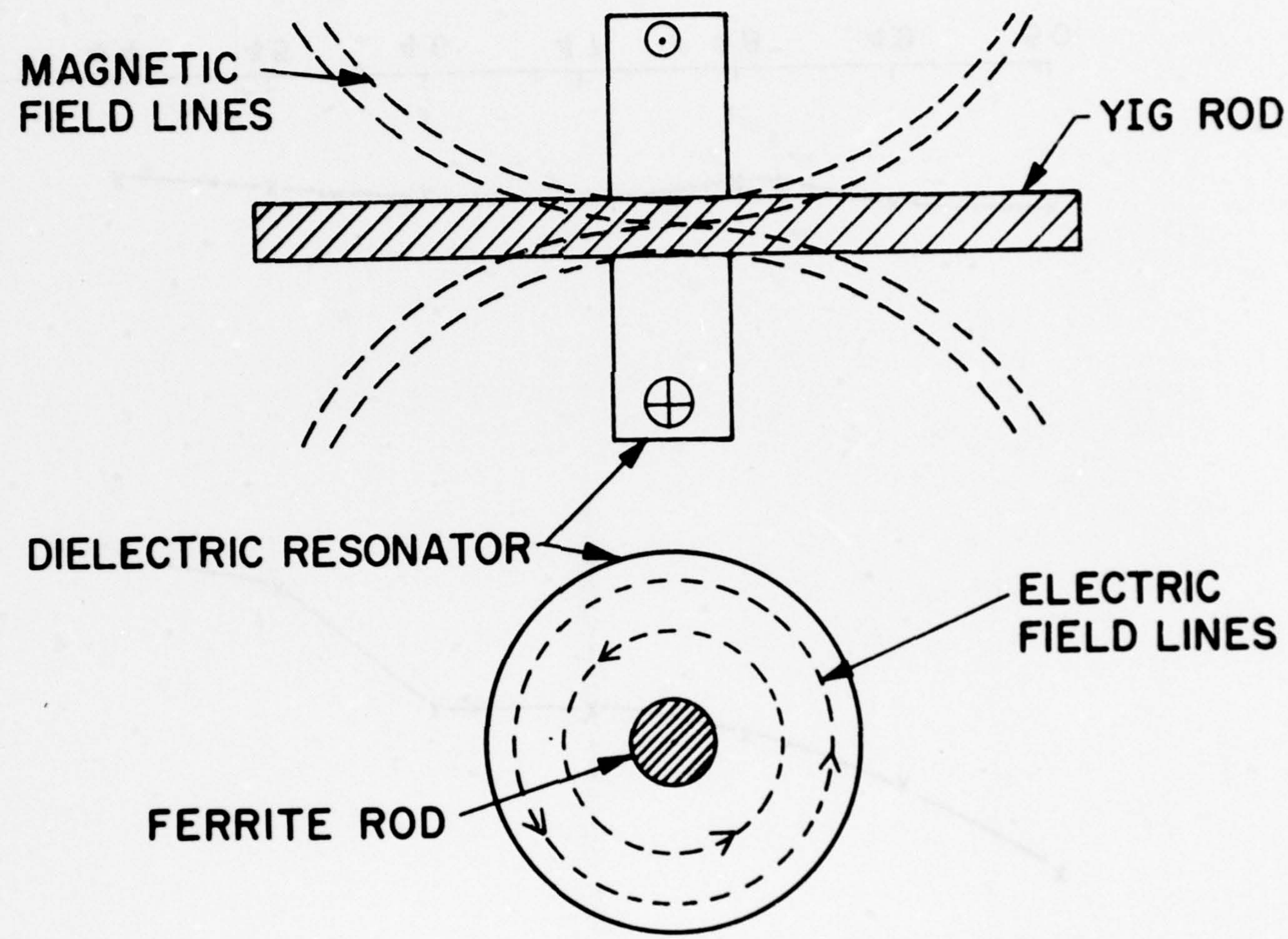

FIGURE 6 - MAGNETIC FIELD CONFIGURATION IN DIELECTRIC RESONATOR

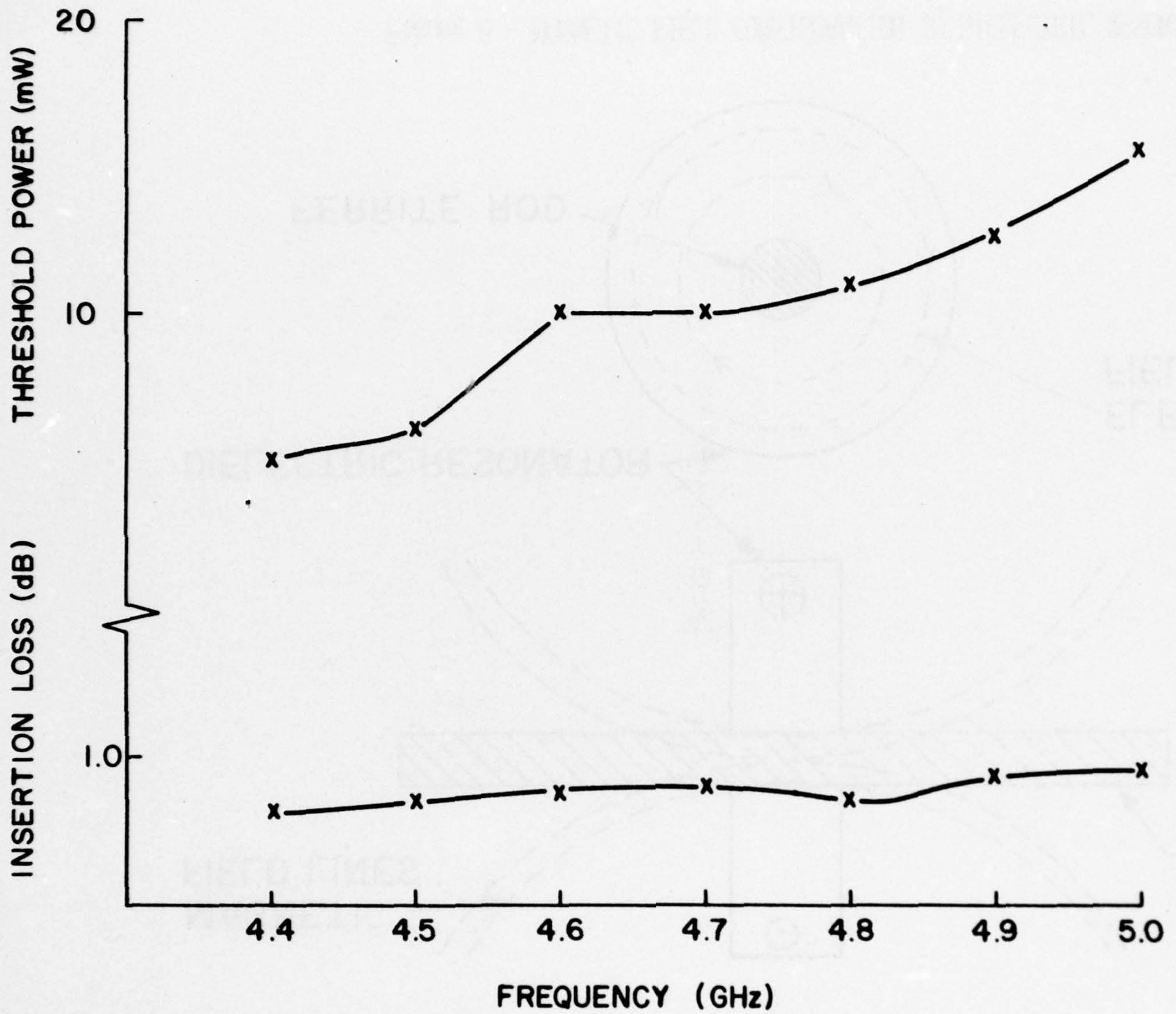

FIGURE 7 - INSERTION LOSS AND THRESHOLD POWER AS A FUNCTION FREQUENCY

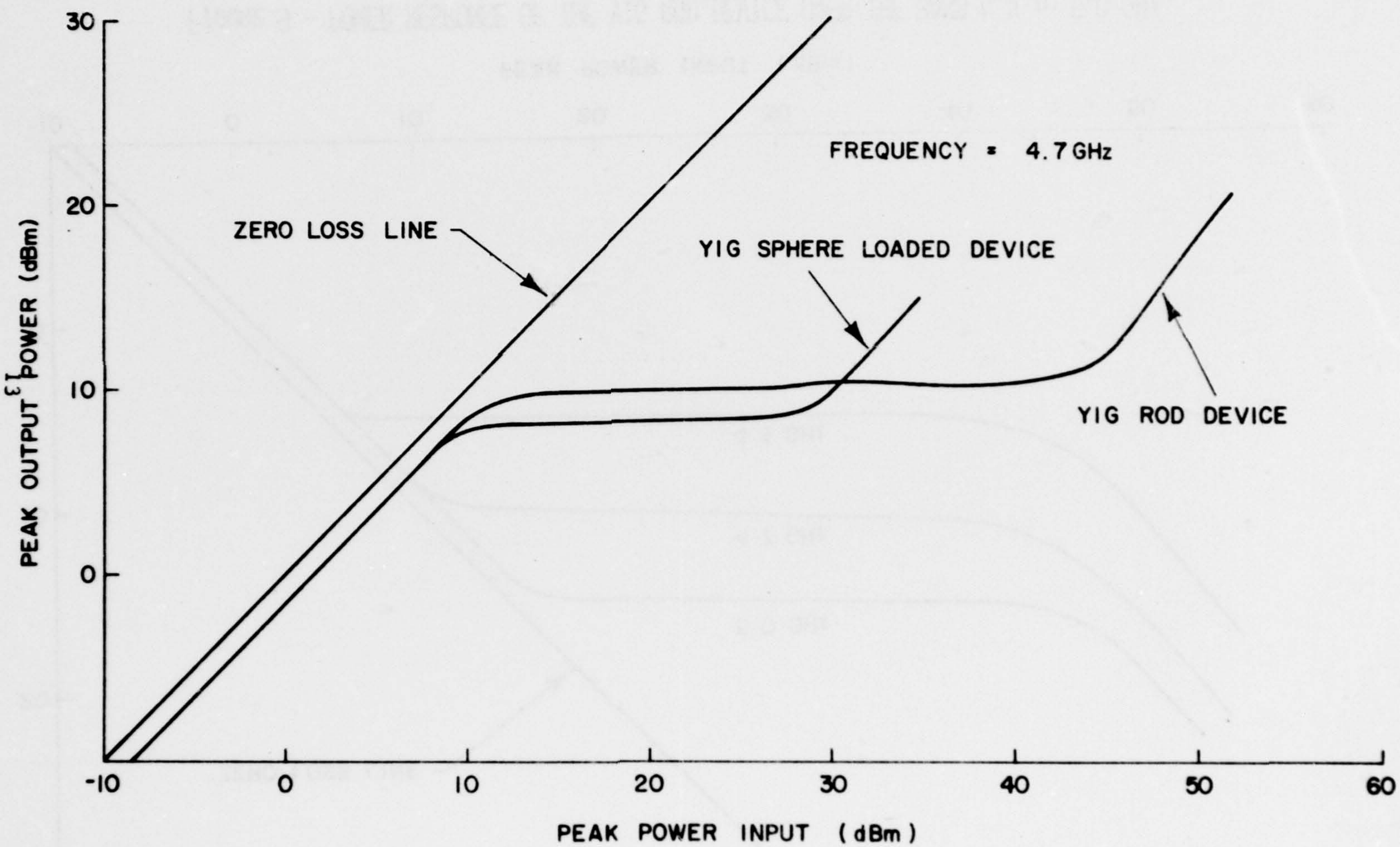

FIGURE 8 - POWER OUTPUT VS POWER INPUT FOR BOTH YIG ROD AND YIG SPHERE DEVICES

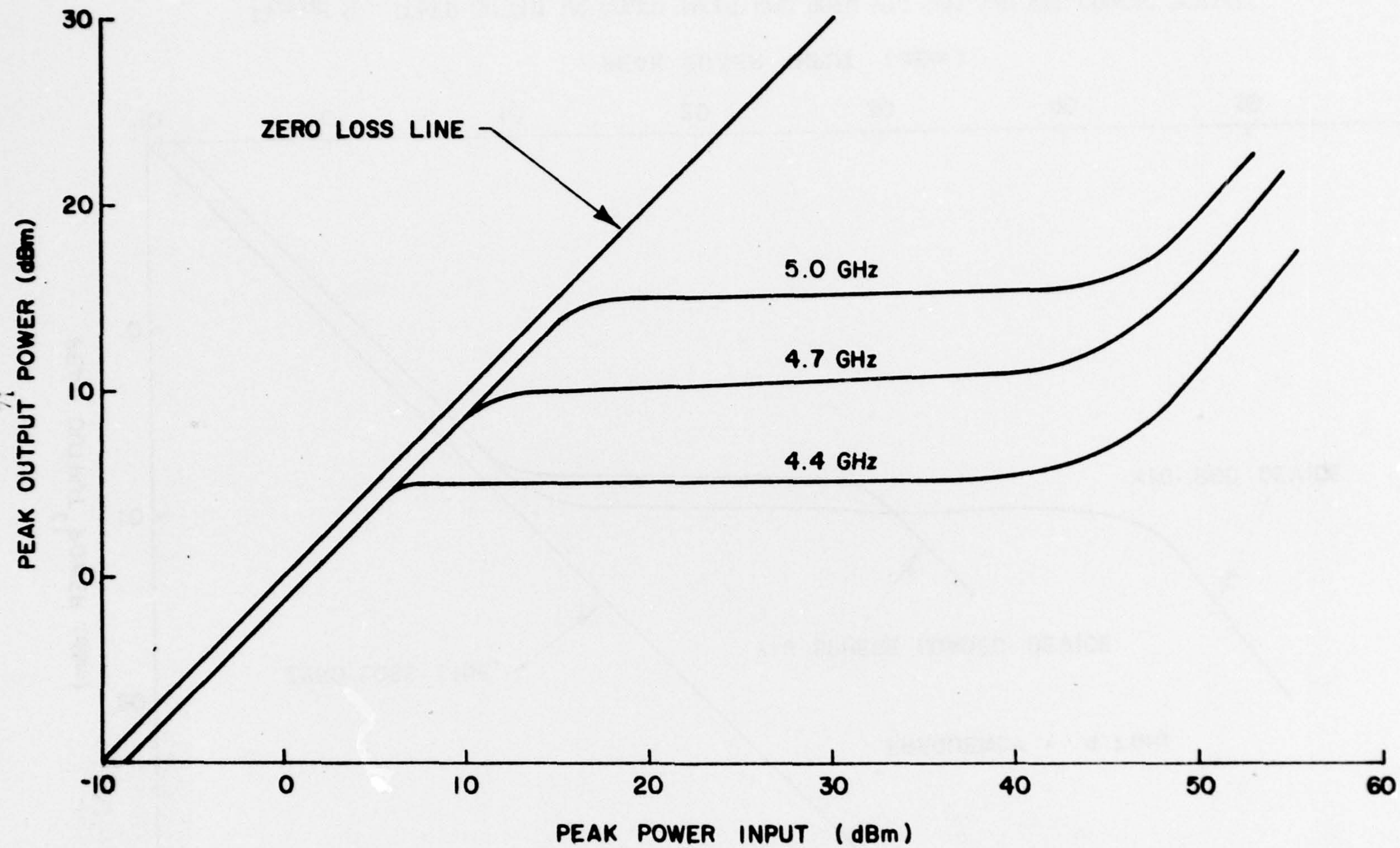

FIGURE 9 - POWER RESPONSE OF THE YIG ROD DEVICE OVER THE BAND 4.4 TO 5.0 GHz